AN OPTIMIZED LATTICE FOR VERY LARGE ACCEPTANCE COMPACT STORAGE RING

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Abstract

Combining a circular storage ring and a laser wakefield accelerator (LWFA) might be the basis for future compact light sources and advancing user facilities to different commercial applications. Meanwhile the post-LWFA beam is not directly suitable for storage and accumulation in conventional storage rings. New generation rings with adapted features are required. Different geometries and ring lattices of a very large-acceptance compact storage ring operating between 50 and 500 MeV energy range were studied. The main objective was to create a model suitable to store the post-LWFA beam with a wide momentum spread (2% to3%) and ultra-short electron bunches of fs range. The DBA-FDF lattice with relaxed settings, split elements and optimized parameters allows to open the dynamic aperture up to 20 mm while the dispersion is limited and the sextupole strength is high. The proposed machine model could be a basis for further, more detailed design studies.

INTRODUCTION

R&D on laser plasma acceleration is pursued with the aim to clear up key issues on the feasibility of a new generation of very compact, cost-effective accelerators and sources of synchrotron radiation for present and future users [1]. Laser Wakefield Accelerators (LWFA) feature short bunch lengths and high peak currents, combined with a small facility footprint. This makes them attractive as injectors for synchrotron light sources, as the length of the emitted photon pulse is directly proportional to the length of the emitting electron bunch. LWFA with their intrinsically short bunches would, therefore, allow to study processes on a much faster time scale than currently possible with the bunch lengths customary for synchrotron radiation source storage rings.

Furthermore, for wavelengths longer than the length of the emitting electron bunch, the photon emission becomes coherent [1]. Thus, the intensity of terahertz (THz) to infrared radiation increases dramatically. LWFA bunches would therefore allow to extend the spectrum of coherent synchrotron radiation in the THz to mid-infrared range, a region currently difficult to access with high intensity and high repetition rates. The combination of a circular storage ring and a laser wakefield accelerator might be a basis for a new generation of compact light sources and advancing user facilities to different commercial applications including multi-user medical applications etc.

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Meanwhile the post-LWFA beam is not directly suitable for storage and accumulation in conventional light source

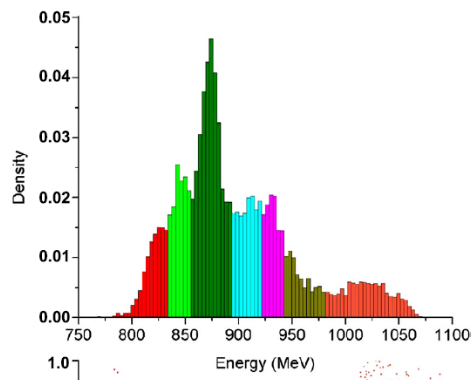

Figure 1: Histogram of energy distribution of electron beam after Laser Wake Field Accelerator, taken from [2]. Central peak energy is 875 MeV. Energy spread of main spike (green slices) 25 MeV well exceeds beam parameters at existing light sources.

facilities [2]. A histogram of the energy distribution of an electron beam after LWFA shown in Fig.1 is taken from [2]. The wide energy distribution is not of Gaussian shape. The energy spread of the main spike of the post-LWFA electron beam is 25 MeV at the central peak energy 875 MeV, and it well exceeds beam parameters at existing light sources. Anticipated full width at half maximum of the main peak approximated by a Gaussian shape is FWHM=3% (σ_p=1.2%). As a consequence, the initially ultra-short electron bunches will quickly be elongated in existing storage rings. Due to the expansion of electrons in the plasma "bubble" with large divergence and momentum spread the effective normalized beam emittance will grow significantly [3]. Growth of the normalized emittance should lead to an increase of bunch length due to synchro-betatron coupling in dispersive sections of a ring [4].

STORAGE RING

One should answer the question if it possible to accept a reasonable part of the e-beam after the LWFA for further storage, manipulation and accumulation in a dedicated ring. Before building post-LWFA facilities based on new generation circular rings one should provide experimental "proof of principles" on possible operation with beams after a laser wake-field accelerator.

A dedicated storage ring with adapted features should be built and tested. Experimental "proof–of-principles" of stable rotation of ultra-short (fs) bunches, storage of a wide-momentum spread beam in circular rings would be a solid ground for further R&D on LWFA facilities.

Extensive studies of possible configurations of very large acceptance compact storage ring (VLA-cSR) have been done at KIT [5] and the results are presented here.

Main objectives of test storage ring operating in an energy range of 50 to 500 MeV are following:

--study stable rotation of 10 to 100 fs ultra-short bunches

--store single spikes of e-beam of 20–200 pC charge and possibly, up to 1 nC

--store beam of wide momentum spread (σ_p=1–2%)

--operate with beam of emittance $\varepsilon \leq 30$ nm·rad (rms)

In order to fit the abovementioned requirements the ring should satisfy the following features:

--momentum acceptance of the ring should be more than ±6% to accommodate wide beam

--ring dispersion must be small (D<25 cm) to fit large energy spread beam in bending sections of a ring

--the dynamic aperture should be large >±15mm to allow the stable rotation of a wide momentum spread beam

--option for phase compressors of chicane type and laser stochastic units installed in straight sections of a ring

--the compact ring should be fitted in existing FLUTE bunker

Parameters of ring are listed in Table 1. The 50 MeV test bench facility FLUTE [6] will be used as ring injector. Beam parameters after FLUTE can be tuned to be similar to those after the LWFA while LINAC bunches more stable and reproducible. The synchrotron radiation damping time exceeds 20 s at a beam energy of 50 MeV and it is considered as slow adiabatic process.

More than 40 versions of compact lattices versions based on DBA, DBA-FDF, TBA, 5BA cells etc. were analysed so far.

Table 1: Parameters of the VLA-cSR Ring (relaxed settings)

Parameter	3Q-split lattice
Energy range, MeV	50 – 500
Magnetic rigidity, T·m	$B \cdot R$ = 0.167–1.67
Circumference, m	44,112
Ring footprint (FLUTE Bunker),m	13,5 × 13,5
Ring periodicity	4 (two 45° FDF-DBA)
Split DBA super-cell (cell/–cell)	2×22,5° / –(2×22,5°)
Straight sections	4 × 2 m
Momentum compaction	6,03 × 10^{-3}
SR losses/turn (50/500 MeV)	<1 eV / 4,3 keV
Horizontal damping partition Jx	1,397
Damping time $\tau_X / \tau_Y / \tau_l$, seconds	24 / 34 / 21 (50 MeV)
RF frequency / F_{ROT} / h_{RF} (MHz)	3000 / 6.8 / 440
Injection energy/ inj.energy spread	50 MeV / σ_p=2·10^{-2}
Inj.beam emittance(norm/unnorm)	<10 mm·mr/<100 nm·r
Natural emitt/nat.en.spr. (no IBS)	0,18 nm·r / σ_p = 4·10^{-5}
Betatron tunes Q_X / Q_Y	5,844 / 8,461
Phase advance (supercell) hor/vert	μ_X= 2.92π / μ_Y= 4.23π
Natural Chromaticity (per cell)	$\xi_{X/Y}$ = –16/–21 (–4/–5)
Dynamic Accept X/Y(incl. errors)	120/20 (70/10) mm·mr
Beta-functions–middle straight, m	$\beta_{X/Y}$ = 1.8 / 1.2
DBA Dispersion max (distr), m	0.25 (±0.15)
Dynamic Aperture hor / vert, mm	(–14…+18) / (± 6)
Momentum acceptance (bare lat.)	±6÷8 %

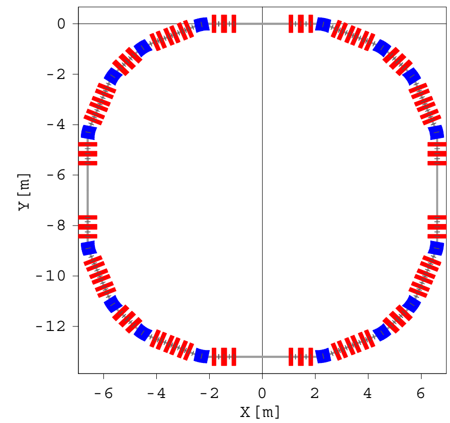

Figure 2: Four fold symmetry model of Very Large Acceptance compact Storage Ring fitted into FLUTE bunker. 22.5° bends are depicted in blue, multipole focusing magnets in red, elements located between quads are not shown [5].

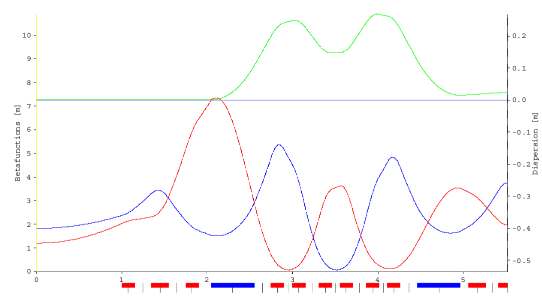

Figure 3: VLA-cSR half-cell (starts middle of straight section). The second half of cell is a mirror reflection. Horizontal beta-function in blue, vertical – in red, dispersion - in green. Bends shown as blue strips, quads - red. High order elements are treated as thin lenses and marked by black lines.

The up to now final version of the ring lattice with relaxed parameters is composed of four equal achromatic sections (Fig.2). Total bending angle of each section is 90°. Bending radius of 22.5° high gradient magnets is 1,273 m, effective length is 0.5 m (Table 2). Due to a lack of space, the compact double bend achromat lattice with split triplets in the dispersive sections has been chosen as a basis for further detailed studies (Fig.3). The lattice model compromises contradictory conditions. A small circumference of the ring leads to strong focusing quadrupoles while the dispersion must be kept small. The acceptance of VLA-cSR is limited by small dispersion and the strong sextupoles required to compensate high negative chromaticity. At the same time, the beam of large momentum spread (σ_p=1÷2%) should be accommodated for stable rotation.

By proper choice of ring lattice, in particular, splitting of strong quads in dispersion sections of a ring we reduce strength of the quadrupoles from 40 down to <16m^{-2}. The "–*I*" condition was realized and chromaticity per unit cell was reduced. Location of horizontal chromatic sextupoles at mirror symmetry position with local maxima of

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Table 2: Parameters of VLA-cSR Magnetic Elements

Magnets, bending angle	C-shape rectangular,22.5°
Bend field level, T	B=0.12–1.2 T
Edge angles (entr/exit)	θ1=θ2=11,25°
Bend. radius/eff. length	1,273 / 0.5 m
Full Aperture, h x v	87×30 mm
Good field region	75×24 mm (10^{-5})
Mom.accept(geometric)	±15 %
Field Index str./grad.	–3,99±0,2m^{-2}/6.7±0.3T/m
Combined function focusing magnets	
Effective length, cm	7.5+7.5 / 10 / 15 / 20
Strength / gradient	< 20 m^{-2} / < 40 T/m
SXT strength / gradient	< 200 m^{-3}/ < 400 T/m^{2}
Octupole str/gradient	<3000 m^{-4}/<5000 T/m^{3}
Misalignment tolerance	±10μ(block)/±20μ(girder)

horizontal beta-function and dispersion helps to reduce integrated strength of sextupoles from 35m^{-2} to <12m^{-2}. The phase advance per cell was adjusted to minimize leading resonance-driving terms. The dynamic aperture of the optimized lattice with split quadrupoles and relaxed parameters was opened from DA_X=±6mm to DA_X≈±20 mm to fit the wide momentum-spread beam (Fig.4). Stable area in vertical plane DA_X=±6mm and injection in axial direction will be possible. Projection of phase space for off-momentum particles is shown in Fig.5. Harmonic sextupoles expand momentum acceptance of the ring to ±6% in the horizontal plane (Fig.5a) and ±8% in the vertical plane (Fig.5b). Harmonic sextupole and chromatic octupole families are applied for non-linear studies, in

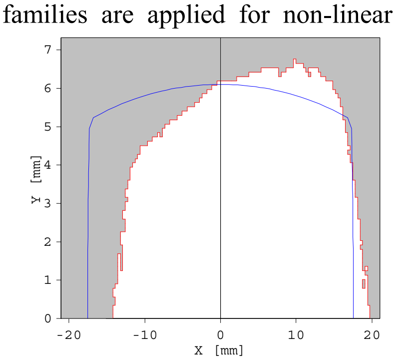
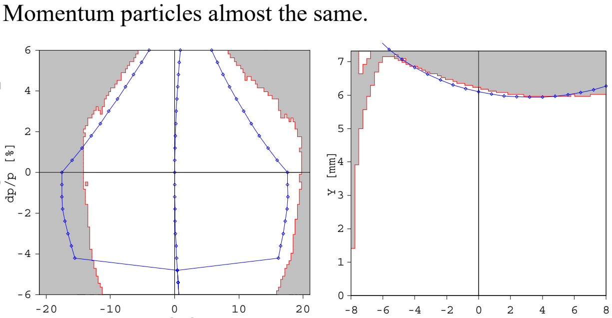


Figure 4: Dynamic aperture of split 3Q lattice in the middle of straight section. OPA simulations. Acceptance of central andoff-Momentum particles almost the same.



(a) (b)

Figure 5: Projection of phase space for off-momentum particles: a) horizontal plane, chromatic sextupoles ON; b) vertical plane, harmonic sextupoles expand momentum acceptance up to ±8%.

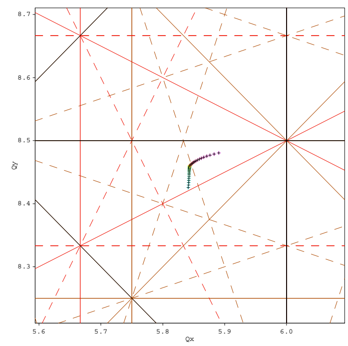


Figure 6: Tune diagram. Combination of sextupoles and chromatic octupoles helps to localize and wrap up foot-print of chromatic tune deviation for particles with momentum offset of up to δp/p≤ ±10%.

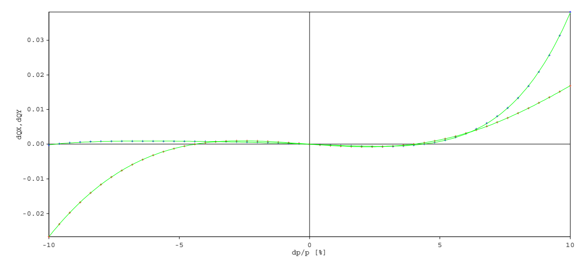


Figure 7: Chromatic octupoles help to reduce deviation of horizontal and vertical tunes to $\delta Q_{X,Y}$ ≤0.03 for off-momentum particles even at δp/p= ±10%. Strength of octupoles was limited to minimize reduction of ring acceptance.

particular, to minimize ADTS, to operate the ring at a negative momentum compaction factor, to manipulate the bunch width and shape. Combination of sextupoles and chromatic octupoles helps to localize and wrap up the foot-print of chromatic tune deviation for particles with momentum offset up to δp/p≤ ±10% (Fig.6). Chromatic octupoles reduce tune deviation to $\delta Q_{X,Y}$≤0.03 for off-momentum particles even at δp/p= ±10% (Fig.7). Strength of octupoles should be limited to preserve ring acceptance. Tight tolerances on misalignments, roll-offs, field errors etc. lead to a design of solid magnetic blocks similar to MAX-IV 3 GeV ring magnets [7].

SUMMARY

Preliminary studies on optimized lattice for a very large acceptance compact storage ring have been done so far. The realization of such a ring would provide a “proof of principles” and solid ground to build next generation synchrotron light sources based on laser wake-field accelerator injectors.

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